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ATM Interruptions Model (AIM) Process Overview

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Air traffic controllers deviate flights from the user's preferred trajectory, to avert impending traffic conflicts and conform to flow-rate restrictions. These deviations are referred to as ATM Interruptions. The efficiency and effectiveness of such controller deviations (interruptions) directly affect controller workload and user costs. Air Traffic Management (ATM) En Route Decision Support Tools (DSTs) have the potential to reduce unnecessary deviations and improve the efficiency with which necessary deviations are implemented by accurately predicting flight trajectories and supporting more efficient clearance decisions.

This report discusses a model designed to assess the impact of, and interactions between, ATM interruptions for conflicts and flow-rate restrictions due to congestion. Important linkages between the integration of metering conformance and separation assurance functions are also part of the model. Through modified input parameters and assumptions, the model has been used to evaluate future ATM DSTs, including the Center TRACON Automation System (CTAS) En Route/Descent Advisor (EDA), and the benefit of en route user-ATM data exchange (EDX) [1-5].

The following sections overview the four primary components of the ATM Interruptions Model (AIM) shown in Figure 1-1: Airspace Simulation, Metering Conformance Model, Separation Assurance Model, and Cost Model. Additionally, the appendix details the format, fields and linkages between the key AIM input and output files.

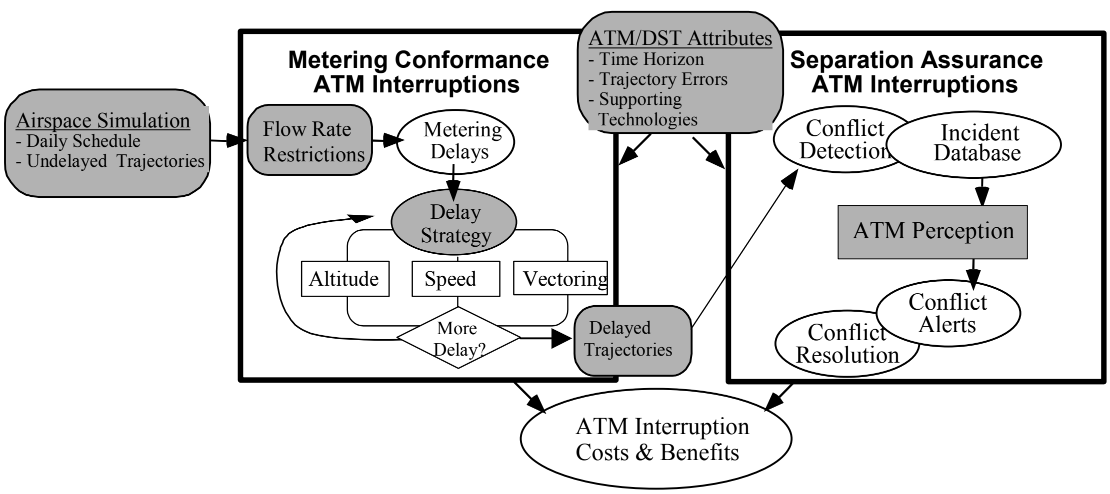

Figure 1-1 ATM Interruptions Model Approach

1 Airspace Simulation

The airspace simulation of AIM simultaneously tracks multiple trajectories in a block of en route airspace. These trajectories represent the geometry and timing of scheduled arrival, departure, overflight and satellite airport operations over a 24-hour period, given initial user preferred flight plans. Standard Instrument Departure (SID) and Standard Arrival Route (STAR) filed routes may be modified to allow arrival direct routing. This simulation generates a set of 4-dimensional (latitude, longitude, altitude and time) "undelayed" trajectories, representing what each flight would do if left alone to fly a user preferred trajectory. These trajectories define a common traffic scenario for ATM interruptions evaluation under the various study cases as described in [3].

1.1 Input Trajectory Data

The input trajectory data used for the model came from the July 14, 1996 flight plans for the continental United States [6]. As such, they represent user-preferred flight trajectories without ATM interruptions imposed to accommodate other aircraft. These data included both header and track data for each flight at a set of NAS-wide airports. The header information for each trajectory, included aircraft characteristics such as flight ID, aircraft type, origin/destination airport, and scheduled arrival and departure times. Additionally, the flight header identified the number of waypoints in the flight trajectory.

The track data include information on latitude, longitude, altitude, time and true airspeed. The format of the input data can be found in the Appendix. The ground speed was available from the input file, but it was determined that the value would be calculated later in the process. The true airspeed data in the input files seem to weather information; however, no detailed weather information was available so, in later processes, the true airspeed was calculated from ground speed using standard day temperatures.

1.2 Creation of Trajectory Databases

To process the data for a single target airport, assumed to be DFW, three files were created from the original input trajectory database:

- **Arrivals** – flight destination was the target airport
- **Departures** - flight origin was the target airport
- **Overflights** - flights where at least one track point passes within 250 nautical miles of DFW, using great circle arc distances.

This subset of flight trajectories was used in the AIM model. These files were parsed with AWK scripts [7], suitable for handling simple mechanical data manipulation tasks.

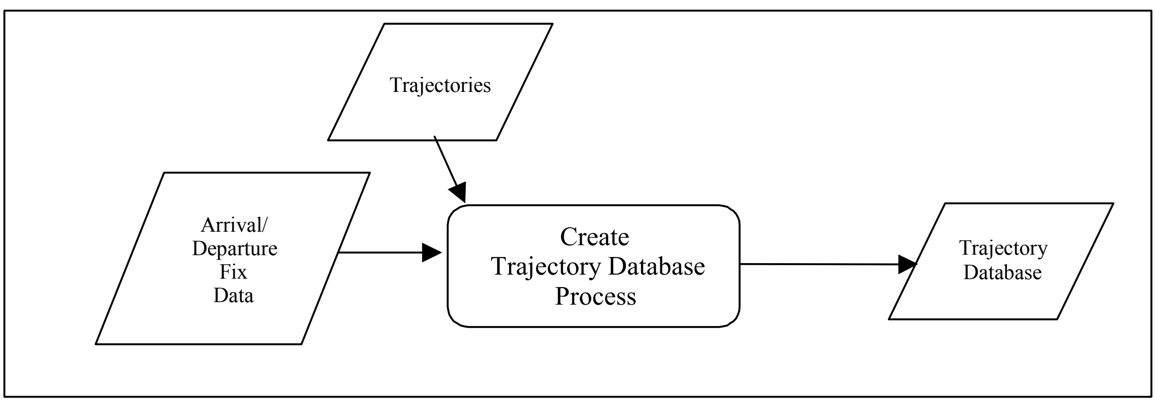

Figure 1-1 Trajectory Database Creation Process File Input and Output

A second AWK program written for previous work [1-2] was used to add new fields to the input trajectory data files composed of a header record and one record for each waypoint in the trajectory. The new fields added to the header record include the aircraft class, azimuth at the departing fix, the radius of the origin airport ring at the

Center/TRACON boundary, the azimuth of the arrival fix and the radius of the destination airport ring at the Center/TRACON boundary.

The new fields added to the trajectory record are waypoint labels, calibrated airspeed (CAS), Mach number, segment flight time, segment flight distance, segment nominal azimuth, segment nominal altitude rate, weight (unused for this project) and flight mode. True airspeed (TAS), and ground speed have been adjusted from the original input as discussed below.

Two new trajectory records were also added to DFW arrivals and departures - one for when the track crosses the arrival/departure fix and one for when the track crosses an imaginary arc 250 nautical miles from DFW, roughly representing the horizontal boundaries of the DFW ARTCC. Trajectory points below 10,000 ft, representing the vertical boundaries of the DFW ARTCC, were also ignored. The resulting trajectory fields are detailed in the Appendix.

1.2.1 Calculation of new fields

1.2.1.1 Aircraft Class

This field contains information about the number of engines, engine type([P]iston, [T]urbo Prop, [J]et) and size classification (for example, Small, Small+, Large, Heavy) determined from the given Aircraft Type.

1.2.1.2 Center/TRACON Boundary Radius

This field represents the average distance of the Center/TRACON boundary from the target airport, encompassing both the departure and arrival metering fixes. At DFW a 40 nautical mile radius was assumed.

1.2.1.3 Center/TRACON Boundary Azimuth

The field described the track azimuth/heading when crossing the assumed Center/TRACON boundary. For departures an array of trajectory waypoints is searched forward from the origin airport to the ARTCC boundary (250 nm from the airport). At each point the track is tested to see how close to the origin airport that segment is. Once a segment is found that crosses the target airport Center/TRACON boundary (40 nm for DFW), the inside and outside points are then used to interpolate a temporary departure track point - latitude and longitude of a point along a great circle path which comes within ≤ 0.5nm of the exact radius. Once this point is found, the heading/azimuth between it and the departure airport is calculated. A similar algorithm is followed for arrivals, searching backwards from the end of destination airport to the ARTCC boundary (250 nm from the airport).

1.2.1.4 Fix Name

This field identifies fixes within the flight track of particular significance. The following fixes are named:

- **TOC/TOD** - Top of Climb (TOC) and Top of Descent (TOD) where the segment altitude changes are less than or equal to 50ft. If the TOC and TOD are coincident, the fix name used is TOCTOD.

- **GIN/GOUT** – Gate-In (GIN) and Gate-Out (GOUT) fixes have been assigned to the added gate in and gate out track lines. These fixes are used only to identify the initial and final waypoint in an overflight trajectory.

- **Arrival/departure metering fix names** - Arrival/departure fix names, as assigned using the algorithm discussed in Section 1.2.2.

1.2.1.5 Fix ID

The Fix ID is a numeric labeling convention developed for key track points of target airport arrivals and departure flight. Current implementation includes IDs at the assumed ARTCC boundary (250 nm from target airport) and the arrival/departure metering fixes. The Fix ID is either a numeric fix or bin assignment.

Numeric Codes for Arrivals Departures

- **ARTCC Boundary** - The Fix ID identifies which 10 degree slice (see Figure 1-2)of the ARTCC boundary ring (defined as 250 nm from the target airport) the track penetrates. The values range from :

  Arrivals: 1000 + BinAssignment
  Departures: 2000 + BinAssignment

Because there are 36 "slices" in the ring, the values range from 1000 to 1350 for arrivals, and 2000 to 2350 for departures.

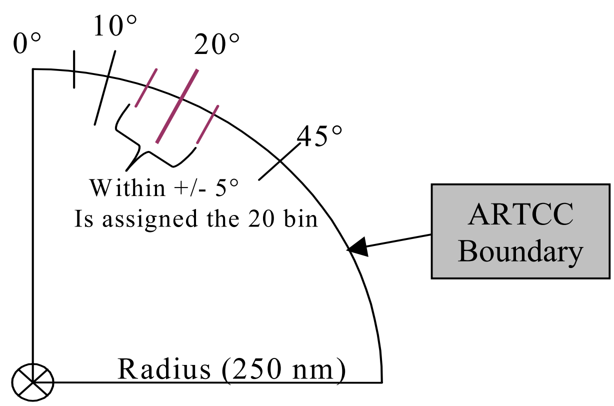

Figure 1-2 Calculating Bin Assignments

Arrival/Departure Metering Fix Crossing Points – The metering fixes have been numbered in an input file with 100s for arrival fixes and 200s for departure fixes.

1.2.1.6 Flight Mode

The flight mode (1-5), representing the flight phase of the preceding flight segment, was set using the following schema:

- **Gate** – 1st and last track point for overflights and removed for arrivals and departures. Conflicts occurring in this phase of flight are not considered in this effort.
- **Taxi** – 2nd track point until the 1st altitude increase, indicating take-off and points following the last altitude change until last track point, indicating landing.

- **Climb** – Take-off to Top of Climb (TOC),
- **Cruise** – TOC to Top of Descent (TOD), and
- **Descent** – TOD to landing

1.2.2 Creating Arrival/Departure Fix Tracks

This algorithm evaluates each target airport arrival and departure and assigns arrival and departure metering fixes. It creates a new trajectory point at this location, describing the trajectory crossing time and metering fix information. A file containing information about the fixes associated with DFW is input into the Create Trajectory Database process. Each record contains a fix name, whether it is an arrival or departure fix, its latitude, longitude, and its range and azimuth from the airport.

For each fix, an imaginary circle, centered at the airport and passing through the fix, is drawn. The arc-length difference between the azimuth of the crossing point of the track being classified and each of the fixes is then calculated. Selection of the appropriate fix is based on finding the fix with the minimum absolute arc length difference $|\theta_1-\theta_2|$.

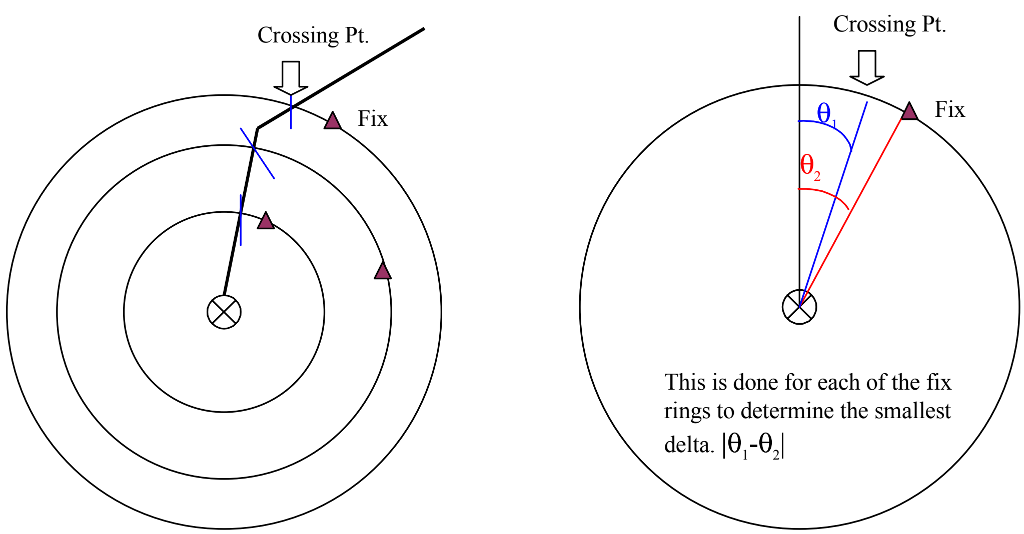

Figure 1-3 Choosing a Fix

Once all the fixes have been checked the result is the one with the minimum absolute arc angle. This point corresponds to the fix assignment. A new point is generated in the trajectory to represent the arrival/departure metering fix crossing. The fields for this new point are interpolated from between existing points, as appropriate, including crossing time, speeds, etc. The fix name field is set to the name of the assigned arrival/departure metering fix.

1.2.3 Creating ARTCC Boundary Trajectory End Points

This algorithm is used to evaluate all flights to determine where each flight crosses the ARTCC boundary, assumed 250 nm from the target airport. It creates a new trajectory point at this location, describing the trajectory crossing time and other fix information.

2 Metering Conformance ATM Interruptions Model

Metering Conformance ATM interruptions reflect flight modifications to realistically absorb the delay necessary to meet airport/airspace capacity restrictions. In the ATM Interruptions Model, the undelayed flights from the Airspace Simulation are analyzed to determine the level of congestion and determine aircraft-specific arrival/departure metering delays. Departure delays are simply delayed pre-departure at the departure airport. The delay strategy employed to absorb the arrival metering delay (a mix of changes to the speed profile, cruise altitude, and routing) depends on the assumed ATM technology employed. The output of this model are the information on the aircraft-specific delay maneuvers employed, and a second set of arrival/departure flight trajectories which reflect these delay maneuvers.

2.1 Metering Delays

A scheduling algorithm is used to determine the amount of necessary arrival/departure delay at the target airport (i.e. DFW). In the case of arrivals, this algorithm emulates the functions of the Center TRACON Automation System (CTAS) Traffic Management Advisor (TMA) tool. The metering delay for each flight is calculated by a given set of rules ensuring both legal fix separation and TRACON Airport Acceptance Rates (AAR), limiting the combined arrival/departure fix crossing rate.

The arrival and departure trajectory databases described in Section 1.2 are the input to an AWK script that performs the delay calculation.

The AWK script process is as follows:

1. Find the Arrival/Departure metering fix associated with each flight,
2. Order the flights by increasing crossing time at each metering fix
3. Determine the delay if the separation rule is violated, and
4. Determine any additional delay if the TRACON AAR is violated

After the script has processed every flight, it outputs a file that contains the Aircraft ID, metering fix, scheduled time of arrival at the fix, new delayed time of arrival at the fix and the delay time.

2.2 Delay Absorption

The Metering Conformance Delay Absorption algorithm modifies arrival and departure trajectories to delay them under metered conditions. Four possible adjustment methods are used to alter the trajectory of particular flights so that the proper amount of delay (calculated as described in Section 2.1 above) is inserted into the track, using delay methods reflective of the decision support tool (DST) scenario under study. The four adjustment methods are summarized below:

- **Speed Adjustment (SA)** - Reduce aircraft CAS speed at current altitude on current path length, to a minimum speed subject to rounding/increment limitations keeping an equal relationship between cruise and descent speeds.
- **Altitude Adjustment with or without speed adjustment (AA/ASA)** – Reduce aircraft altitude on current path, to a minimum of the ARTCC Sector floor, (24000’/23000’ depending on direction). Allow for incremental (2000’) or maximum

altitude changes (minimum altitude or bust). In some scenarios, speed is also allowed to change at the new altitude, employing the method to modify descent speed in coordination with any cruise speed changes.

- **Vectoring (Heading) Adjustment (VA)**– Increase path length, using simple 1-sided vectors (one turn off the route, one turn back on), at constant altitude and speed, up to a maximum heading change and subject to rounding/increment limitations.
- **Time Shift Strategy (TS)** – Last resort method, assumes delay is absorbed in upstream ARTCC (arrivals) or at departure airport (departures), essentially shifting undelayed waypoint crossing times to absorb any remaining delay. That is, all of the points in the track are delayed by an amount equal to the residual delay

For departures, only the Time Shift strategy is employed. Although the delay strategy does not differ among technology cases, the imposition of delays results in a more realistic timing of departure flights into the airspace. For Arrivals, two different ATM technology cases are used: Free Flight Phase 1 (FFP1) and EDA. Each case has a specific Delay Absorption strategy which differs in (1) the ordering of the above 4 methods; and (2) the parameters used within each adjustment method. In general, the 4 adjustment methods are employed in a case-specific order, each attempting to insert the necessary delay into the track such that the flight meets its required time of arrival (RTA) at the arrival fix. If the first strategy does not insert sufficient delay, the second strategy is employed to absorb the remaining delay, etc., until all required delay is absorbed.

Figure 2-1 displays the logic that was used to determine if an adjustment to the original trajectory is needed and then performs the various methods to absorb the delay if necessary.

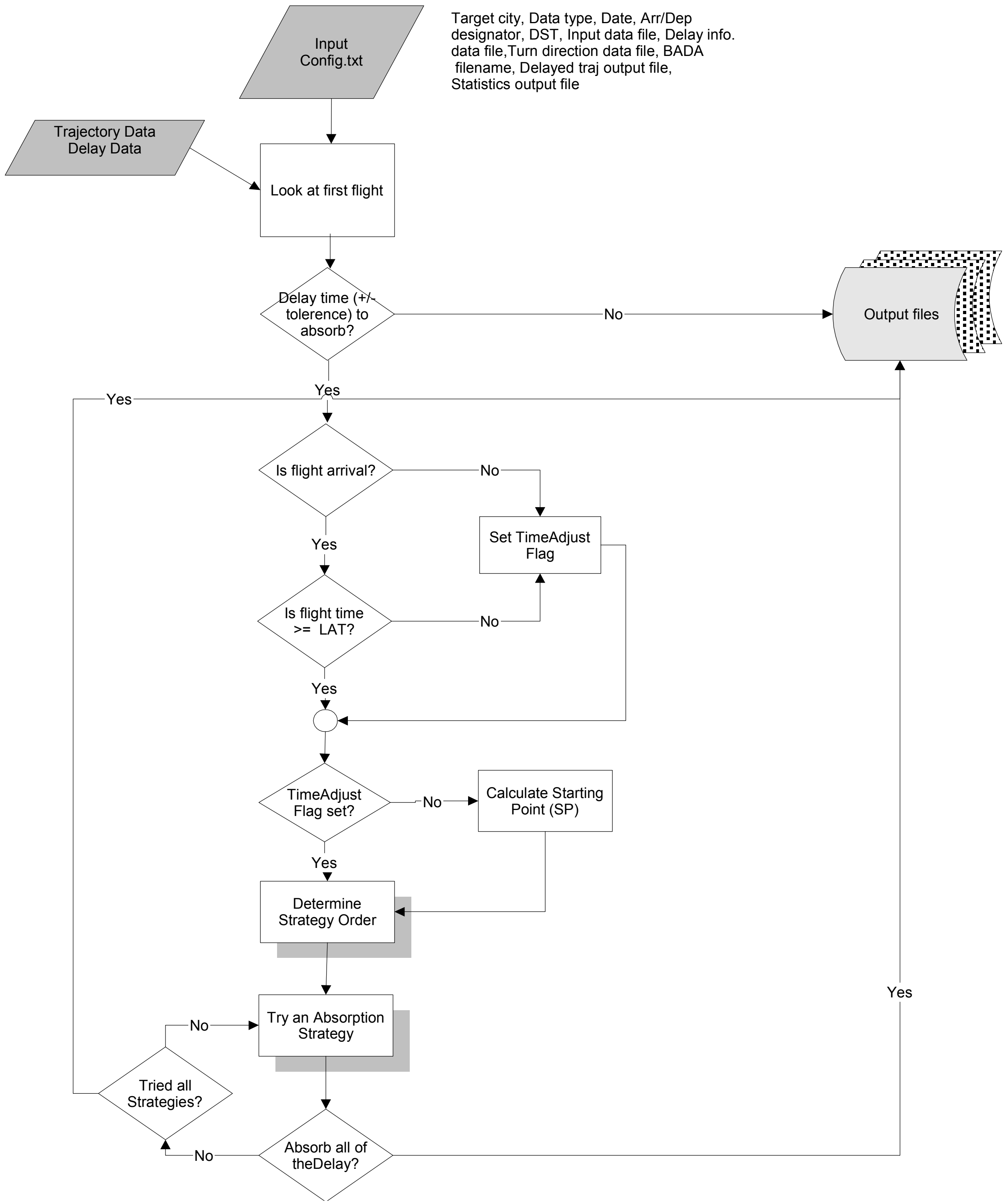

Figure 2-1 Delay Absorption Strategy Process Flow

As shown in the figure, before the Delay Absorption strategies begin, the trajectory is checked for the following conditions.

1. Does this flight have any assigned delay time? If not, do not adjust the trajectory and go to the next flight.
2. Is this a departure? If so, assume ground delay and only use the Time Shift strategy.
3. Is the flight time less than the time horizon (or look-ahead time, LAT)? If so, only use the Time Shift strategy.

The first step of the actual Delay Absorption process is to identify the starting point (SP) on the track at which the procedure will begin. This is done by starting at the bottom of the descent (BOD) or the arrival fix and moving backwards along the track for the length of the case-specific time horizon, and adding a new point to the trajectory. Then, based on the case-specific assumptions, determine the order of the delay absorption methods to use. A general discussion of each method follows.

2.2.1 Speed Control (SA)

Figure 2-2 Speed Adjustment (SA) Strategy Flow

As shown in Figure 2-2, the first step in the Speed Adjustment (SA) method is to identify the current cruise and descent speeds. These speeds are the upper boundary for the algorithm. The lower boundary is determined by minimum speeds, defined as a function of best endurance speeds (CAS). Best endurance speeds for the fleet were represented by aircraft speed data from the European BADA model [9]. BADA "low" cruise speeds were tabulated for 52 Aircraft types, and assumed to approximate 10 kts above best endurance speed.

Cruise/descent speed combinations are developed by incrementing each speed according to case-specific. This strategy is used for all cases. Under these conditions, the best cruise/descent speed combination is found that will absorb as much as possible, but no more than the required delay. At this point, a case-specific error is added to the Cruise speed to reflect controller error in developing the speed solution. This error will increase the cruise speed and lead to less delay being absorbed. Note that the combined altitude/speed changes of ASA method (see Section 2.2.2) will override SA speed modifications. This only occurs under the EDA case if the flight is a jet and the SA procedure did not absorb all of the delay.

2.2.2 Altitude Control (AA or ASA)

Altitude Adjustment (AA) is the method used for the FFP1 scenario. Figure 2-3 shows the logic used in performing this method to absorb arrival delay. The more complex Altitude/Speed Adjustment (ASA) method is used for the EDA/EDX case. Note that AA and ASA methods only apply to jet aircraft.

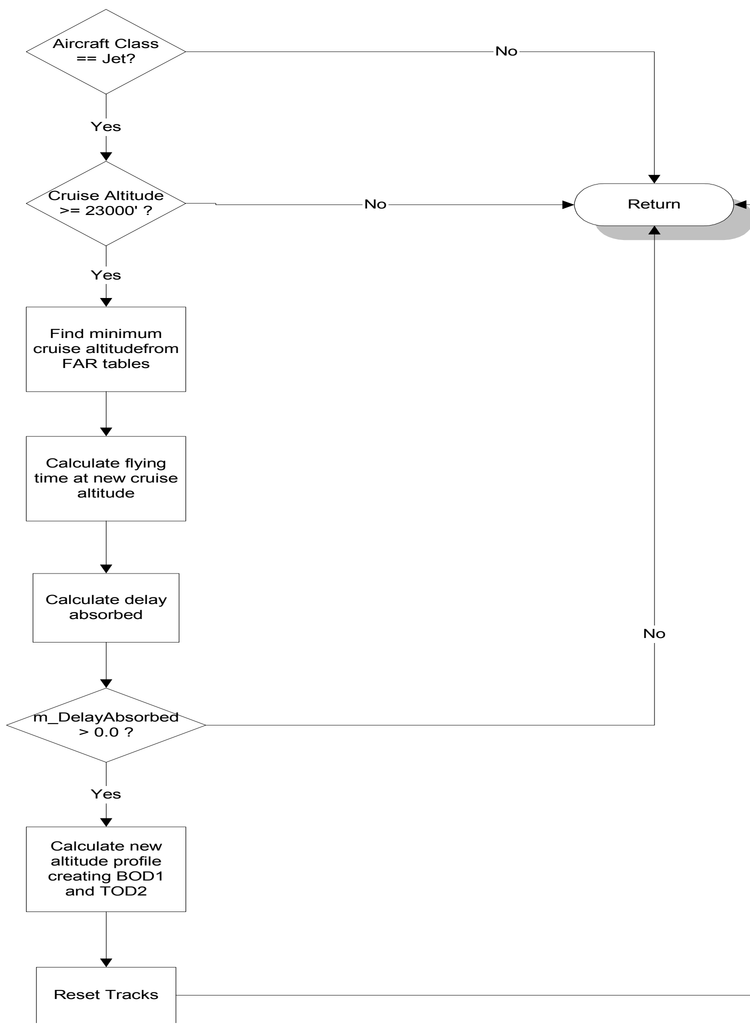

Figure 2-3 Altitude Adjustment (AA) Strategy Flow

With Altitude Adjustment, the best-permitted altitude is dropped, keeping CAS constant. With Altitude Speed Adjustment, the flight is dropped to the best-permitted altitude at minimum speed and then the speed is increased to absorb the correct amount of delay. The best permitted altitude for AA is the altitude that absorbs as much but no more than the required delay. For ASA, the best-permitted altitude is the altitude that absorbs just over the required delay (so the aircraft can speed up to match required delay). The permitted altitudes are a set of user-defined altitudes for eastbound and westbound traffic under EDA/EDX cases and only the minimum altitudes of these lists for the TMA case. The assumed altitude lists, reflecting FAA altitude separation standards [8], follow:

> Eastbound: FL230, FL250, FL270, FL290, FL330, FL370, FL410, FL450
> Westbound: FL240, FL260, FL280, FL310, FL350, FL390, FL430

Figure 2-4 shows the more complicated logic of the ASA algorithm.

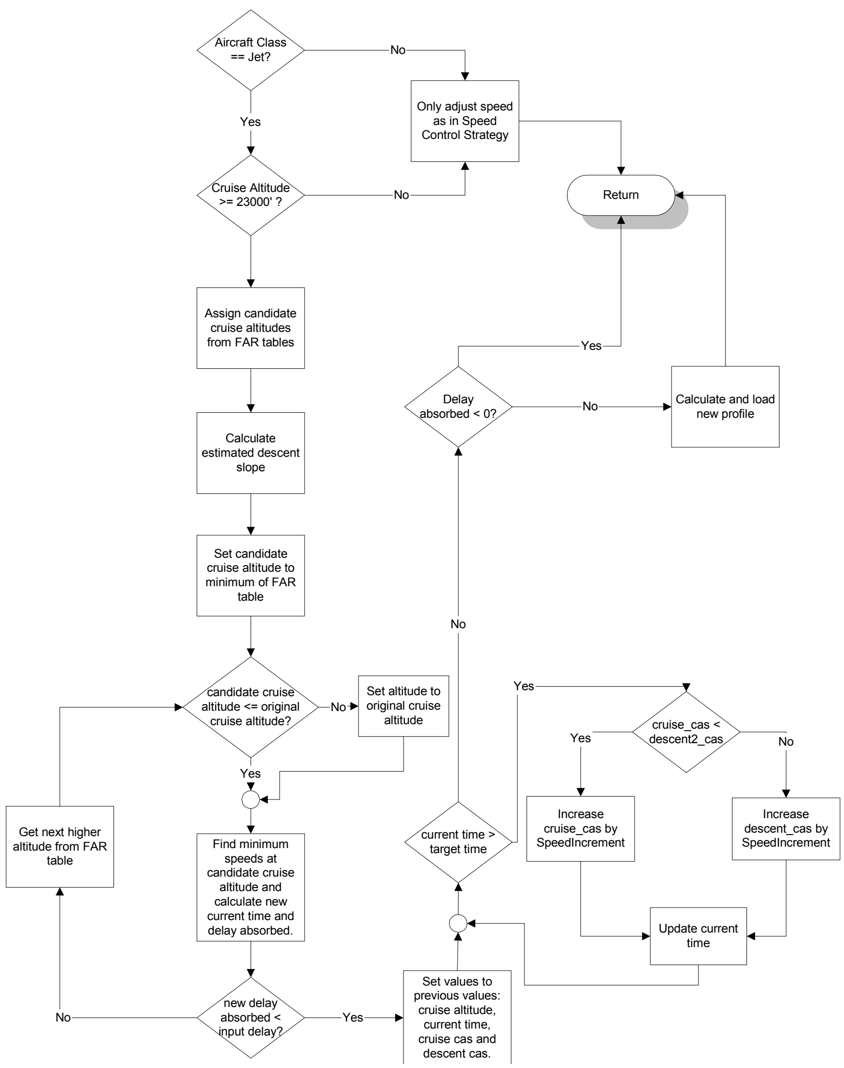

Figure 2-4 Altitude Speed Adjustment (ASA) Strategy Flow

2.2.3 *Vectoring Adjustment (VA)*

Under the vectoring adjustment (VA) method, a simple out and back vector is added to the trajectory during cruise. As shown in Figure 2-5, if a step descent has not been added to the trajectory through the AA or ASA methods then vectoring begins at the Starting Point (SP), defined previously by the case-specific time horizon, and ends at the top of descent (TOD). If the trajectory has a step descent, the vectoring takes place on the cruise segment between the bottom of the first descent (BOD1) and the top of the second descent (TOD2).

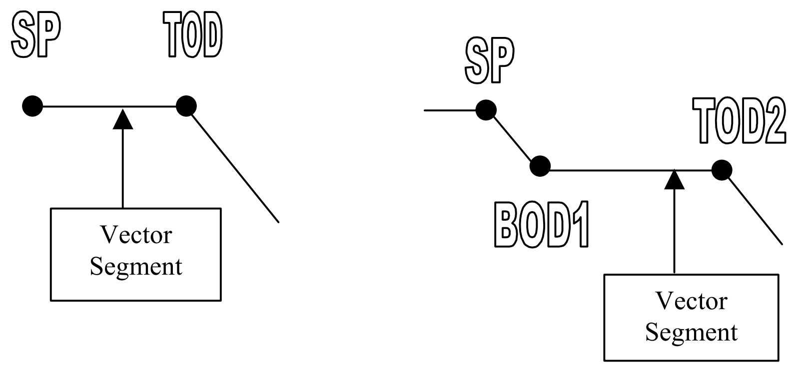

Figure 2-5 Determination of Trajectory Segment for Vectoring Method

An optimal heading, up to a maximum of 60°, is found that will absorb as much delay as possible, but no more than the remaining required delay. This heading is measured relative to a line drawn from the starting point (SP or BOD1) to the top of descent (TOD or TOD2), rounded to nearest 1°.

Figure 2-6 shows the logic flow of the Vectoring Adjustment (VA) delay absorption method.

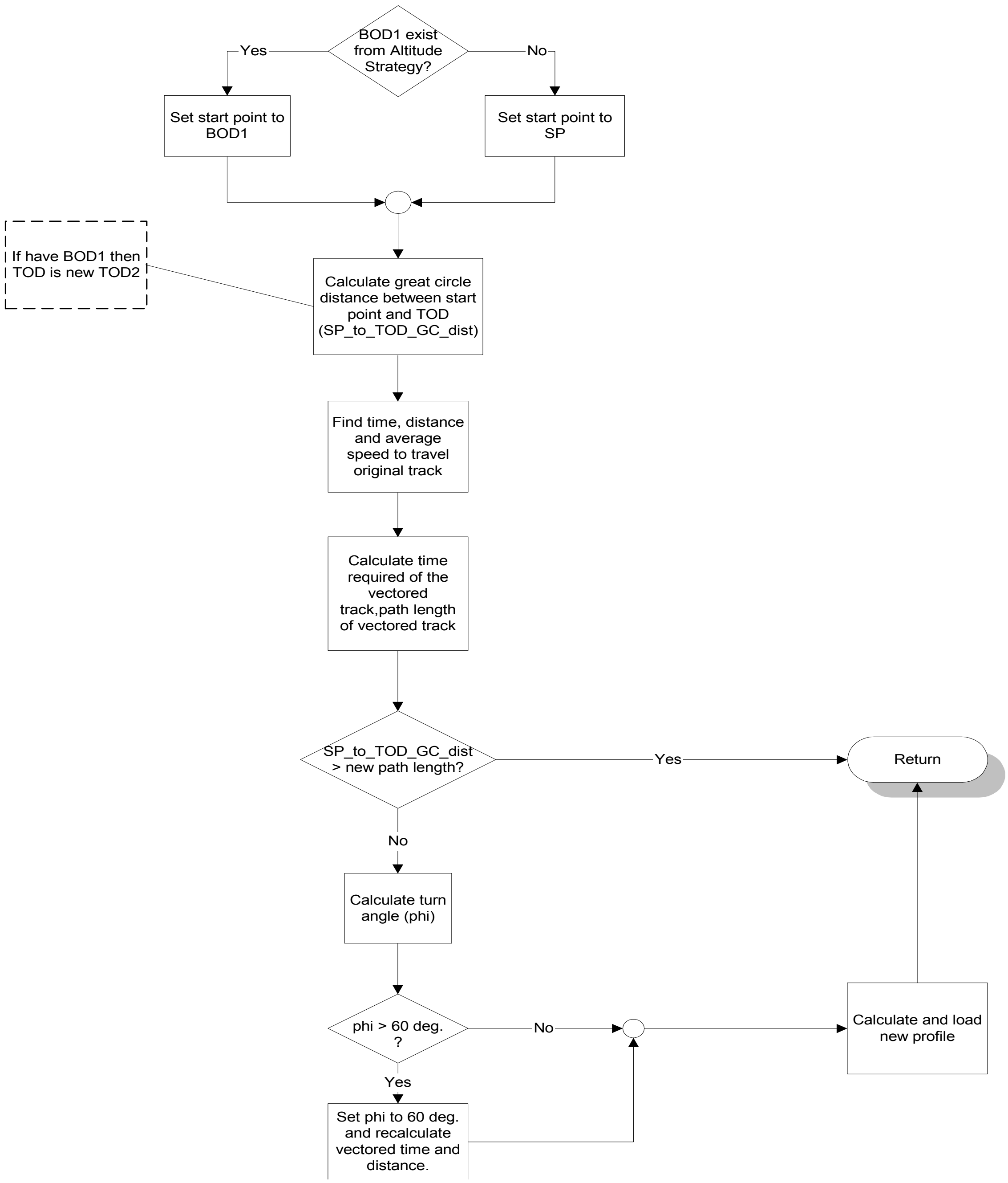

Figure 2-6 Vectoring Adjustment Strategy Flow

The VA algorithm assumes a simple turnout heading and a symmetric turnback heading during the cruise flight segment, which returns the aircraft exactly at its TOD. If the turnback maneuver is not timed properly, the aircraft will either be early to the TOD, requiring additional delay on descent, or late, unnecessarily increasing the overall vectoring path length. The program calculates this error for cost purposes (see Section 4) but does not implement the error in the updated delayed arrival trajectories.

2.3 Output

Two output files are created in the Metering Conformance ATM Interruptions Model - a set of new delayed trajectories, and statistical output from the delay methods applied.

2.3.1.1 Delayed Trajectory Database

The trajectories output from the Metering Conformance ATM Interruption Model have the same format as the undelayed Trajectory database, but now reflect the changes made to absorb the required delay time. These delayed trajectories, in addition to unaltered overflight trajectories, are used as input to the Separation Assurance ATM Interruptions Model.

2.3.1.2 Statistical Output

An arrival and departure output file is generated, containing statistics on the methods and flight changes imposed in the Metering Conformance delay absorption processes. It is used in calculating the costs of the delay absorption maneuvers as well as in assisting in validation of the program function. The statistical output file format differs between arrivals and departures due to the fact that only the Time Shift method of delay absorption was used for departures.

The information saved for departures includes the aircraft ID, aircraft type, aircraft class, delay time, scheduled departure time, scheduled arrival time, assigned departure fix, and UTC time at departure fix crossing.

For arrivals, the same basic flight information is gathered along with the arrival metering fix (bottom of descent) altitude. Cruise and descent speeds, cruise altitude, top of descent (TOD) information and starting point information for both the original trajectory and the adjusted trajectory are also saved with the arrival statistics. Finally, information is collected for each strategy, such as how much delay time was absorbed, original and final speeds and altitudes, etc.

3 Separation Assurance ATM Interruptions Model

The assessment of Separation Assurance ATM interruptions involves both detection, and resolution of ATM perceived conflicts. The trajectories that were created in the Airspace Simulation and the Metering Conformance processes reflect en route activity where no attempt was made to resolve traffic conflicts other than airport metering requirements. These trajectories allow for the identification of actual and potential conflicts that would occur without ATM separation assurance intervention, (as would be embedded in actual radar track data).

Initially, a **conflict detection** method is employed in AIM to step through the simulated trajectories and identify all actual and possible traffic conflicts. The resulting Incident Database identifies all aircraft pairs perceived by ATM as requiring intervention. The database also identifies attributes of the aircraft pair's point of closest approach (PCA).

These detected incidents may or may not be perceived as conflicts by ATM. ATM is assumed to intervene and interrupt trajectory pairs whose PCA falls below an acceptable controller spacing, as perceived by a conflict probe tool. One component of **ATM perception** is the accuracy of the expected PCA attributes reported by the conflict probe at the tool's assumed time horizon, given technology-specific trajectory prediction errors. A second component of perception is identification of Acceptable Controller Spacing (ACS), a function of both the required FAA minimum separation and an intentional buffer, used to limit separation violations, given trajectory errors. When the ACS is compared with the conflict detection reported PCA attributes of each event in the Incident Database, a Probability of Conflict is calculated, which identifies the likelihood that a controller would perceive the incident as a conflict (PCA falls below ACS) requiring intervention. Because of uncertainty and lack of integration with other DST functions, intervention may result in correct or false alerts, and non-intervention may imply a missed alert, that will need to be resolved tactically.

For each perceived conflict of the Incident Database, a **conflict resolution** cost is defined. This fuel cost penalty represents the cost to avert a conflict using vectoring resolutions, at the tool-specific time horizon. The particular conflict geometry and severity of the incident are taken into account when resolving conflicts. Missed alerts are resolved in a tactical manner by assuming a more expensive shorter time horizon. The ATM perceived probability of conflict is calculated based on tool-specific ATM perception, and that value is used to weight the overall separation assurance interruption cost of each incident. Although the resulting resolutions are not rigorous solutions to these conflicts, they provide an approximation of the cost of resolving the various conflict situations.

Creation of the Incident Database involves several steps that are encapsulated in a series of applications and data processing methods, including Conflict Detection, ATM Perception, Conflict Resolution, and Separation Assurance Interruptions Tabulation & Costs.

Inputs to the this series of processes include the following sets of data:

- Trajectory Data
- ATM Perception Uncertainty (position error)
- Resolution Cost Input

Trajectory data include DFW overflights passing through the Center, and arrivals and departures representing flights that have been subjected to the various delay strategies. ATM Perception Uncertainty is used in the calculation of Acceptable Controller Spacing values which vary by mode of flight (climb, cruise, and descent) and ATM perception tool (FFP1, EDA, EDX, etc). Resolution cost inputs consist of fuel consumption costs per nautical mile and are tabulated for each mode of flight and by aircraft classification. Aircraft are classified by size, type (jet, prop, turboprop), and number of engines.

In general, two outputs result from the AIM Separation Assurance model. These are (1) an Incident Database, including PCA, ATM perception, and resolution costs for each perceived conflict, used in identifying Separation Assurance Interruptions count and costs, and (2) a conflict resolution validation & verification (CRVV) file, which details the incident-specific vectoring resolution for validation purposes. The AIM Separation Assurance software steps are discussed in more detail in the remainder of this section.

3.1 Conflict Detection

Conflict detection software systematically examines the arrival, departure, and overflight trajectories, and identifies potential conflicts between them. It reports conditions of the detected conflict incidents in the Incident Database, such as point of closest approach (PCA). These incidents are used as input to the ATM perception and conflict resolution application.

3.1.1 Conflict Detection Input Parameters

The input parameters for the conflict detection software include the following:

- Protected Airspace Zone (PAZ) dimensions, including radius (nm) and height (ft)
- window of time (slice of time during the day) to examine the trajectories (min),
- the time to advance the window each pass (min), and
- the time step (min).

Detection software input files include the following::

- Trajectory Data, and
- Predicted Position Accuracy Tables (for calculating Acceptable Controller Spacing)

3.1.1.1 Input Flight Trajectories

Flight trajectories are the key input to the AIM detection code, and consist of a set of three files including arrival, departure, and overflight trajectories for the targeted airspace (i.e. Ft. Worth ARTCC) during the simulation period (i.e. typical day). As currently employed, the arrival and departure trajectories represent the metered flights output from the Metering Conformance component of the ATM Interruptions model. The overflight trajectories represent all other flights that enter the targeted airspace (defined in this study as above 10,000 ft and within 250 nm of DFW)

A conversion utility (convert.exe) was written to generate trajectory data files in a format suitable for the Conflict Detection software. This utility transforms the latitude and longitude waypoint data from the files into Cartesian coordinates with the X and Y axes parallel to the East and North directions, respectively, and in units of nautical miles. DFW is placed at the origin of this coordinates system. Altitude is converted from ft to nm. The X and Y values are used to determine the distance to DFW and to exclude aberrant waypoints outside the target airspace.

3.1.1.2 Protected Airspace Zone Dimensions

Aircraft are said to be in conflict when either aircraft enters the Protected Airspace Zone (PAZ) of another aircraft. The size of this cylindrical region, described in Figure 3-1, is determined by the conflict detection software at each timestep.

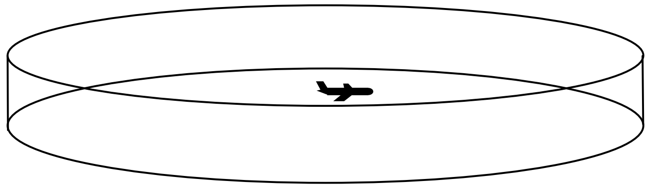

Figure 3-1 Aircraft Protected Airspace Zone (PAZ)

The PAZ radius is set to a fixed value (12 nmi for this work). This value exceeds the FAA minimum separation standards [8] to ensure that all potential incidents that ATM might perceive as a conflict are included in the incident database list. PAZ height is dynamically calculated for each conflicting flight pair at each time step based on altitude (sensitive to FAA criteria for above/below FL290 [8]) and flight mode (sensitive to different safety buffers applied to cruise/transition flights). Conflicts are filtered out if the vertical separation at the point of closest approach is greater than the vertical Acceptable Controller Spacing (ACS). If the PAZ height differs between the two conflicting aircraft (because they are at different altitudes or flight modes), the more constraining value is used (i.e. the larger PAZ height).

3.1.1.3 Time Window and Time Step

The conflict detection code determines relative position information at each time step, so the time step used determines the spatial resolution with which conflicts may be detected. In general, the time step should be a small fraction of the time it takes for an aircraft to travel the length of the smallest PAZ size encountered. Additionally, a window advance time is set so that successive time windows overlap. The following window values were assumed:

- Time Window – 300 minutes
- Time Step – 0.1 minute
- Time Advance – 290 minutes

3.1.2 Detection Algorithm

The detection code is an expansion of an algorithm created in previous research [10]. The detection software creates a rectangular workspace representing a region large enough to contain all waypoints from the trajectory database (in this work roughly 500 nm X 500 nm X 10,000 ft). This workspace is sliced into a grid of cells or bins. For a given aircraft, a list of aircraft with which it is in potential conflict is created by inspecting all other aircraft that are in the same bin or a neighboring bin. Thus not all aircraft pairs need to be compared at each time step. The software checks the relative position of aircraft in this list during a time window and determines if any aircraft is violating another's PAZ, indicating a conflict condition. If so, the conflict attributes are collected for that instant in time.

After the trajectories are compared, the time window is advanced, and the list of aircraft in conflict is updated based on the new aircraft positions. For any pair of aircraft, a conflict condition may exist for many time steps. The detection software begins by assuming that the first point of conflict is the Point of Closest Approach (PCA) and collects PCA related data. If the aircraft are still in conflict in the next time step, the conflict attributes of the two points in time are compared. The data from the time step that represents the lesser separation between the aircraft is retained, and the program continues on to the next time step. When the program terminates, the conflict records representing the least separation are retained as the PCA and stored in the incident database output.

As used here, Point of Closest Approach (PCA) is defined as the vertical and horizontal separation when the aircraft are at their minimum horizontal separation while either aircraft is in the PAZ of the other, which is not necessarily the same point at which the aircraft are closest physically.

3.2 ATM Perception Calculations

Each incident identified in the conflict detection program is assessed to determine ATM's perception and probability of interruption based on case-specific technology parameters. One such parameter is the trajectory prediction accuracy of ATM conflict probe decision support tools. Additional perceived conflict probabilities are determined to represent the case where ATM's perception is inaccurate because the aircraft is not following its flight plan. Once calculated, these ATM perception attributes are stored with the associated incident in the incident database. These attributes are used to determine the tabulation and weighted resolution cost of the separation incidents, as discussed in Section 4. The ATM Perception software calculates the following perception attributes for each incident, with the results included in the incident database:

- Horizontal Acceptable Controller Spacing
- Vertical Acceptable Controller Spacing
- Perceived Miss Distance Error
- Probability of Perceived Conflict
- Off-Flight Plan Probability of Conflict

3.2.1 Input Parameters

The ATM perception software uses the attributes of the same trajectories that were input to the detection software and the incident list generated by that software, and stores these data in the incident database. All other perception values are calculated from the inputs listed below:

- ATM Trajectory Prediction Errors by flight mode (climb cruise and descent), (nm)
- FAA Separation Minima (vertical and horizontal) [8] (nm/ft)
- Incident PCA Attributes (identified during conflict detection)

The position accuracy for the various flight modes is combined with general FAA imposed spacing requirements to determine ATM perception attributes.

3.2.1.1 ATM Trajectory Prediction Errors

Some error is inherent in trajectory prediction using ATM automation with this error dependant on the level of ATM technology assumed. As used in the model, ATM trajectory prediction error (position in nm) is defined as a combination of predicted position accuracy as a function of the time horizon of the predicted trajectory. These values represent the prediction accuracy of assumed ATM/DST technologies and are used in the model's ATM perception calculations. In the model, prediction errors are defined by aircraft flight mode (climb, cruise and descent segments for arrival, overflight, and departure operations) at the conflict point of closest approach (PCA). Additionally previous analyses [3] assumed a 12-minute time horizon for all cases. The break-down by flight mode allows the model to be sensitive to differences in predictability during cruise and transition flight modes. Details of the separate trajectory prediction accuracy modeling, derivation, and resulting predicted position errors can be found in Reference [3], including the calibration of arrival descent errors to CTAS field observations.

3.2.1.2 FAA Separation Criteria

En route, the FAA nominally requires a 5 nm horizontal separation between aircraft. [8] FAA vertical separation requirements vary depending on altitude, with 1000 ft of separation required for aircraft at/below 29,000 ft and a more constraining 2000 ft of separation required above 29,000 ft. These spacing values are never realized because of uncertainty in the ATM determination of the location of an aircraft. Thus AIM imposes another buffer to account for trajectory prediction uncertainty.

3.2.1.3 Incident Point of Closest Approach (PCA) Attributes

Point of Closest Approach (PCA) attributes comprise a key output of the conflict detection software. These attributes include horizontal and vertical miss distances, time, and the flight mode of the aircraft at the point of conflict.

3.2.2 ATM Perception

The ATM perception attributes are calculated for each detected incident. These ATM perception attributes are stored, as additional incident attributes, in the associated incident database.

Note that although both the horizontal and vertical Acceptable Controller Spacing (ACS) values are calculated in the ATM perception software, the vertical ACS value was also calculated and used in the detection code. The vertical ACS value was used to remove detected conflicts that would not be considered conflicts in the resolution code.

3.2.2.1 Horizontal Acceptable Controller Spacing (ACS)

The nominal FAA imposed horizontal separation minimum is augmented with a safety factor dependent on ATM trajectory prediction error and the minimum separation factor.

The horizontal minimum separation factors were estimated based on current system horizontal ACS observations (8 nm) and estimated ATM trajectory prediction position errors.[1] Note, if the calculated ACS values tied to the conflict aircraft differ, the more constraining of the values for the two aircraft is saved in the incident database.

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[1] That is the current system (observed) ACS values are combined with current system estimated ATM trajectory prediction position error values and FAA minimum en route separation (*Rule*) to derive the minimum separation fraction (*n*).

3.2.2.2 Vertical Acceptable Controller Spacing (ACS)

The vertical minimum separation factors were estimated based on current system vertical ACS observations (no safety buffer in cruise, 1000 ft safety buffer in climb and descent) and estimated ATM trajectory prediction position errors.[1] Note, if the calculated ACS values tied to the conflict aircraft differ, the more constraining of the values for the two aircraft is saved in the incident database.

Additionally, aircraft crossing in opposite directions during cruise flight mode (using FAA hemispherical rules) at >2000 ft. vertical separation were not considered in conflict.

3.2.2.3 Perceived Miss Distance Error

The error in the predicted PCA miss distance is determined using Equation (3.3) based on the ATM trajectory prediction position errors of the pair of aircraft involved in the incident.

3.2.2.4 Probability of Perceived Conflict

Perceived conflict probability represents the likelihood that ATM would strategically perceive the incident as a conflict requiring interruption. Assuming an aircraft is following its ATM flight plan, the perceived conflict probability is calculated.

When ATM perception is inaccurate because the aircraft is not following its nominal flight plan, an off-flight plan probability of perceived conflict is calculated.

3.3 Conflict Resolution

The conflict resolution software outputs a series of conflict resolution maneuvers and their associated costs under various conflict criteria. To do so, it performs two functions: (1) identification of initial conditions for the conflicting aircraft pair, where conflict resolution maneuvers will begin, and (2) calculation of the resolution maneuver and associated costs. Both functions rely on inputs of flight trajectory and case-specific time horizon and ATM Acceptable Controller Spacing attributes. As currently specified, only horizontal vectoring resolutions are used. Conflict Resolution maneuvers are output into a conflict resolution V&V (CRVV) file for software validation, while conflict resolution costs are added, as additional conflict attributes, to the incident database.

3.3.1 Resolution Input Parameters

The resolution software employs the attributes of the trajectories, including aircraft class and trajectory points, input to the detection and ATM perception software modules, the PAZ dimensions, and the incident list generated by the detection software. All other resolution values are calculated from the inputs listed below:

- Time Horizon
- Fuel Burn Cost Rates

3.3.1.1 Time Horizon

The conflict resolution time horizon, separate from the metering conformance time horizon, is the period of time between when a potential conflict is perceived and the aircraft are actually in a conflict situation. This value varies depending on errors associated with tools at the disposal of the ATM. Three types of conflicts are considered in the conflict resolution process: correct alert (CA), missed alert (MA), false alert (FA), and affect strategic/tactical time horizon. For correct or false alerts, the nominal Time Horizon is a user defined input reflecting the look-ahead time of the ATM conflict probe automation. For a missed alert, the conflict is not perceived within the normal time horizon, so a tactical resolution is necessary, assumed to be 5 minutes prior to the conflict start.

3.3.1.2 PAZ Dimensions

The three types of conflicts affect the PAZ dimensions for conflict resolution. Correct and missed alerts assume the PAZ dimensions reflective of the horizontal and vertical ACS values, calculated in the ATM perception software, discussed in Section 3.2. For false alerts, ATM is resolving a conflict that would not actually occur, and the PAZ size is increased to the PCA miss distance from the detection software, to force a resolution. One nautical mile is added to the PCA value to ensure that a resolution is calculated.

Table 3-1: Inputs Parameters for ATM Perception Calculations

Conflict Type	Correct Alert (CA)	Missed Alert (MA)	False Alert (FA)
Time Horizon	12 or 19 minutes depending on perception tool (TMA, EDA, EDA w/EDX)	5 minutes	12 or 19 minutes depending on perception tool (TMA, EDA, EDA w/EDX)
PAZ Radius	Horizontal Acceptable Controller Spacing	Horizontal Acceptable Controller Spacing	Actual Miss Distance plus 1 Nautical Mile

3.3.1.3 Aircraft Fuel Burn Cost Rates

Reading in a file that contains fuel cost rates as a function of altitude and aircraft class produces a cost table. The PCA altitude of the conflict is used to interpolate the cost from the table's discreet altitude levels for a given aircraft class. This cost per nautical mile is applied to the added distance traveled in the resolution maneuver relative to the unresolved path to determine the total cost of the resolution maneuver.

3.3.2 Identification of Initial Conditions

Due to the design of the resolution algorithm, the aircraft trajectories must be in a steady state. Therefore, to define the initial conditions of the aircraft conflict prior to conflict resolution, both aircraft trajectories are backed up along a straight line a distance greater than the aircraft will travel during the time horizon. This is a steady-state back up from the PCA as identified in the detection software as shown in Figure 3-2. This point is well before the point at which the aircraft will begin the resolution maneuver. The point after this at which the maneuver will begin varies depending on the conflict category (correct, missed, false alert). A tactical solution must be employed in the case of a false alert.

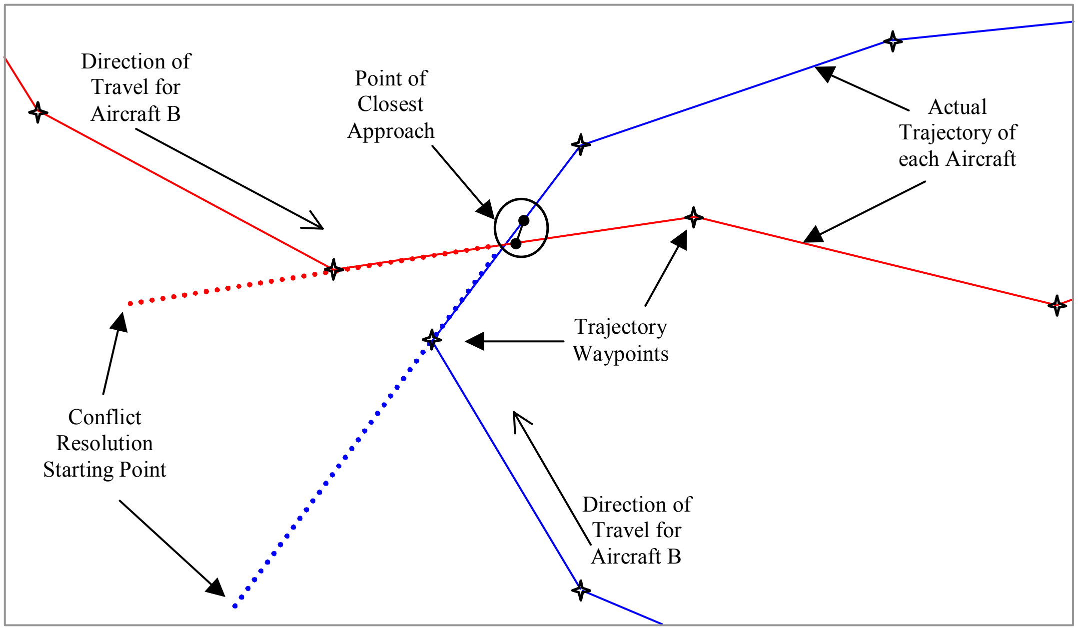

Figure 3-2 Identification of Initial Conditions for Conflict Resolution

The Time of Conflict is the time between the point of first conflict and the point of closest approach. It is calculated by dividing the distance traveled while the aircraft are in conflict by the relative velocity of the aircraft. The distance traveled while in conflict is the Horizontal Acceptable Controller Spacing that defines how close the aircraft can be before being considered in conflict.

From the point of closest approach, each aircraft is backed up along the particular direction of flight that the aircraft are flying at the time of conflict. This time is 20 minutes before the first instant in which the aircraft are determined to be in conflict.

3.3.3 Calculation of Resolution Maneuvers

Conflict resolution is investigated assuming a series of standard vectoring maneuvers [11-12]. Solutions are piecewise continuous line segments where speed and heading are kept constant along each segment. The algorithm searches for line segments that can replace a portion of the flight path in the vicinity of the conflict providing a path that geometrically passes the PAZ of the other aircraft. The velocity of the defending aircraft (aircraft of interest) is resolved in the frame of reference of the intruder aircraft (conflicting aircraft). The relative velocity of the defending aircraft is altered to avoid the intruder aircraft. In cooperative resolutions, both aircraft's headings are altered such that their combined heading change provides the proper separation.

Twelve resolution maneuvers and associated costs are calculated for each incident in the incident database. These are defined by the conflict category (correct, missed, false) and type of resolution. The four types of resolution may be grouped into two categories:

1. **Horizontal** Resolution attempts to resolve the conflict through a change in heading. If a cooperative maneuver is specified then the headings of both aircraft will be affected. The Horizontal Resolution will produce a **Front Side and a Back Side** maneuver.

2. **Vertical** Resolution attempts to resolve the conflict through a change in climb rate. If a cooperative maneuver is specified then the climb rates of both aircraft will be affected. The Vertical Resolution will produce a **Top Side and a Bottom Side** maneuver.

Although the resolution software finds vertical (altitude) resolutions, these were not used in the analysis. Additionally, either cooperative or non-cooperative solutions are available using the resolution algorithm. Non-cooperative costs are 2-3 times larger than cooperative costs. Cooperative costs were used since not all conflicts can be feasibly resolved non-cooperatively.

3.3.4 Calculation of Resolution Cost

The resolution cost is determined simply by calculating the estimated additional fuel costs required to fly the solution flight plan returned by the conflict resolution software. The solution is generally modeled by diverting the aircraft vertically or horizontally and then returning it to the flight plan. The additional travel distance will incur the added fuel cost. The fuel burn rate is determined based on flight mode, altitude, and aircraft class. Solution routes that have a path length of over 500 nm are rejected.

The solution has the same beginning and end points as the original unresolved (and conflicting) trajectory, so calculating the difference in distance traveled is trivial. The final cost is a function of this travel distance difference and the cost of the fuel per pound.

3.3.5 Resolution Cost Output

The resolution costs calculated by the conflict resolution software are included in the Incident Database (IDB) output and are used in the Separation Assurance Cost Model. The cost values are also output to the Conflict Resolution Verification and Validation (CRVV) output files. Again, although vertical (top side and bottom side) resolution costs are calculated and reported, these values are not used in the analysis.

3.3.6 Resolution Maneuver Output

In addition to the Incident Database, a set of files is produced by the conflict resolution software to help validate the solutions that are returned. This includes background information on the conflict (from the incident database), aircraft initial conditions prior to resolution, and the conflict resolution track of each aircraft.

3.3.7 Merging of Delayed and Undelayed TMA Incident Databases

For the baseline FFP1 case, the conflict probe tool is assumed to not know the trajectory changes made when the controller clears an aircraft using the metering conformance delay absorption clearances. As a result, the SID/STAR FFP1 Incident Database (IDB) output is a combination of the "perceived" TMA Undelayed (flight plan routes) and "actual" Delayed (delayed routes) Incident Databases. The combined output file has the same format as all other Incident Databases.

- The delayed and undelayed FFP1 Incident Databaseswere combined. In the procedure described below, (hPCA, vPCA) are the horizontal and vertical distance between aircraft at the Point of Closest Approach (PCA), while (hACS,vACS) describe the horizontal and vertical Acceptable Controller Spacing (ACS).

- If the same incident (same aircraft) occurs in both databases, then the incident attributes from the delayed file are used, including hPCA, vPCA, hACS and vACS values, and the Probability of Conflict from the undelayed file.

- If an incident is found only in the undelayed database (this represents a false alert), then the incident attributes and the Probability of Conflict from the undelayed file are used. The hPCA is set to 999 (undefined), the hACS to 5.000 and vACS to 1000 feet, if the vPCA was less than or equal to 29000 feet. If the vPCA is greater than 29000 feet, the vACS is set to 2000 feet.

- If an incident is found only in the delayed database and its hPCA is less than its hACS value (this implies a missed alert), then the incident attributes, including the hPCA and hACS values from the delayed file are used. The Probability of Conflict and the OFPProbability of Conflict are set to 0.0. If an incident is found only in the delayed database and its hPCA is greater than or equal to its hACS value (this implies no conflict), then the incident is not included in the combined database.

4 ATM Interruptions Cost Model

The number and cost of ATM Metering Conformance and Separation Assurance interruptions are identified in an analysis of the metering statistics output and incident databases, respectively. This includes the type and cost of delay maneuvers employed for metering conformance interruptions and additional ATM interruptions to ensure separation assurance, as perceived by ATM. Fuel costs of resolving all ATM perceived conflicts from the 24-hour incident database are tabulated. By comparing the costs of ATM interruptions of a baseline to an enhanced ATM system, expected average per interruption fuel cost savings are identified reflecting the single day simulation findings.

These AIM results are annualized and extrapolated to the NAS by applying the interruption rates simulated in the AIM model results to annual operations at likely deployment sites.

4.1 Metering Conformance Interruptions Costs

AIM allows the user to evaluate the impact of alternate arrival metering conformance delay absorption strategies. No change was made to departure metering conformance or to the amount of metering delay required per aircraft. The key inputs to the tabulation and cost calculations are the arrival and departure statistics output of the AIM Metering Conformance simulation.

The Metering Conformance cost model makes calculations to estimate arrival and departure time and fuel costs for each interrupt. Interruption frequency is estimated as the number of delayed flights as required to meet airport/airspace capacity restrictions (see Section 2). This interruption rate is essentially the number of operations in the airport rush periods and is not assumed to change with technology enhancement. The average cost per interruption is calculated as the sum of daily time and fuel costs for each flight, divided by the number of interrupted flights.

4.2 Separation Assurance Interruptions Costs

Separation Assurance conflicts are estimated by analyzing the Incident Database (IDB) output from the ATM Interruptions Model (AIM). Only fuel costs are assumed. The AIM model detects potential conflicts, and calculates ATM perception and conflict resolutions for each conflict. The resolution is assumed to avoid the conflict with vectoring. Each Separation Assurance IDB output file is processed in MS Excel format making the calculations/analysis discussed below. These results are then compiled in a summary MS Excel (ResSummary.xls), where further adjustment is made to arrive at the final results, the number, type, and cost of ATM perceived Separation Assurance conflicts. The summary file compares baseline and enhanced AIM runs to arrival at statistics, such as reductions in false/missed alert counts and overall cost savings. The processing of each type of file is identified below.

The Separation Assurance tabulation and cost model makes calculations to estimate interrupt rates and per interrupt fuel costs, used to extrapolate simulation results to annual and NAS-wide level. Interruption frequency is estimated as the sum of all categories of interruptions (correct, missed, and false alert interruptions). The averages per interruption costs are calculated as the sum of fuel costs for each conflict resolution, divided by the number of interrupted flights.

4.2.1 Incident Database.xls file Processing

The processing of the Incident database for each AIM case occurs in this file. The primary objective of this processing is to classify each conflict by type and operations type, and estimate the associated resolution costs.

1. Characterize each conflict with the following attributes:
    - **Pairwise Operations Type** - (e.g. O-O), A=Arrival, D=Departure, O=overflight/satellite airport operations
    - **Pairwise Flight Mode** - (e.g. cl-cl) defined at conflict point of closest approach (PCA), cl=climb, cr=cruise, d= descent
2. Identify the best non-zero horizontal (vectoring) conflict resolution cost (fuel only).

Twelve different costs were calculated for vertical (altitude) backside/frontside maneuvers and horizontal (vectoring) topside/bottomside maneuvers, depending on correct, missed, and false alert criteria. Only the six vertical altitude resoltuions were used in the cost analysis. The minimum non-zero vectoring resolution cost for each conflict type was identified. If no feasible resolution was found, average resolution cost values, discussed in Step 4 were substituted. Resolutions were deemed infeasible if:

- Missed Alert cost was less than Correct Alert cost,
- Correct Alert cost was $0,
- False Alert cost was $0,
- Missed Alert cost exceeded $30 (considered excessive),

- Merge cases, such as Arrival-Arrival, Departure-Departure, and
- Same direction, small relative headings (less than 10 degrees difference)

Incidents with the last two attributes are considered to be outside the theoretical bounds of the conflict resolution algorithm, resulting in excessively protracted and costly resolutions.

3. Calculate the probability of each incident being perceived in various categories:

Correct Alerts (above/below FAA minima), Missed Alerts (above/below FAA minima), and False Alerts, are calculated as follows. The conflict probabilities are calculated for each incident, based on conflict probabilities (Prob_conflict, OFPProb_conflict), actual incident attributes (PCA), Acceptable Controller Spacing (ACS), FAA minima rules (FAARule), and the assumed likelihood of bad intent (*n*% if BadIntent=True). Note the sum of all probabilities should be 100% for any incident.

4. Create Average Cost Table:

Average costs were calculated from flights with valid non-zero resolution costs, as identified in Step 2. Separate average costs were tabulated for correct (CA), missed (MA), and false (FA) alert under each pairwise operations type (i.e., A-A, D-D, A-D, A-O, D-O, O-O). The resulting table was reviewed for the following expected trends:

- All cost categories should decline under enhanced technology cases
- FA costs should not exceed CA costs which should not exceed MA Costs.
- All resolution costs should be of similar order of magnitude, with D-D costs the largest, due to higher climb fuelburn rates.

5. Weighted Incident Cost

The cost of each Separation Assurance ATM interruption was calculated as a weighted average, given ATM perception of the incident. Thus, the correct, missed, false conflict costs of Step 2 are weighted by ATM perception of correct, missed, false, and no action probabilities of Step 3.

4.2.2 ResSummary.xls File Processing

1. Tabulate Separation Assurance ATM interruptions

The number of Separation Assurance ATM interruptions of each category from the daily AIM simulation was tabulated by summing individual conflict perceived probabilities (Step 3 of above IDB process). Thus, each conflict is partially counted in several categories.

2. Review Separation Assurance ATM Interruptions

The number of Separation Assurance ATM interruptions was reviewed relative to the other technology cases, represented by different AIM runs. The following expected trends were assessed, with appropriate corrections made, as required:

- Number of CAs + MAs less than the FAA minima rule should be constant for all cases, provided the run started with the same input trajectories.
- Number of MAs should decline, and CAs increase with enhanced cases

- Number of FAs should decline with enhanced cases, particularly with intent improvements (e.g. reduced off-flight plan routing)
- Overall average cost per interruption should decline with enhanced cases
- FAs should decline significantly

3. Calculate Daily and Per Interruption Separation Assurance costs

The resolution cost of each conflict in the AIM simulation of the 24-hour period at the target airport, as calculated in Step 2 of the IDB process, are summed. This daily cost is divided by the total number of interruptions to identify an average cost per interrupt.

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